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THE EFFECTS OF OIL CONCENTRATION AND DROPLET DIAMETER IN OIL-IN-WATER EMULSION ON STRIP ROLLING

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Summary
A numerical scheme, which allows tracking of the concentration process within both the inlet and wok zones, has been developed. The scheme allowed us to calculate the rolling pressure and friction associated with the process for different emulsion's oil concentrations, λ_{ds} and oil droplets diameter, d_s. Hence the intertwined effect of λ_{ds}, d_s and rolling speed on strip rolling parameters could be analyzed. The result shows that rapid concentration, which occurs in the inlet zone, increases the emulsion's oil concentration sharply. This process effectively transforms the oil into the continuous phase of the emulsion. The analysis of the results also suggests that it is possible to reduce the emulsion oil concentration without detrimental effects on the rolling process. The use of emulsion results in a slight increase in rolling force. Despite this less favorable outcome of using emulsion it is possible to control exit film thickness H_{t2} with an appropriate combination of oil concentration level and droplet sizes.

Keywords: droplet diameter, emulsion, equivalent viscosity, extended Reynolds equation, mixed film lubrication, oil concentration, surface roughness

1 INTRODUCTION
Oil in water (O/W) emulsion is a lubricant composed of oil in the form of droplets suspended in water. It has become a common lubricant in strip rolling applications due to its cost, cooling ability and non-flammable characteristic whilst providing good rolling lubrication. An O/W emulsion generally contains 1% to 5% weight of base oil made of natural, mineral, or synthetic oil with droplet diameter that typically exists in the range from 2 to 20μm, emulsifier agents and water. In producing a certain emulsion it is possible to control the oil concentration, droplet size and emulsion stability through the types of emulsifier used and the emulsifier concentration level [1]. However there has been limited information as to the performance of O/W emulsion of different concentration level and droplet size in terms of rolling performances.

The lubricating mechanism of emulsion has attracted many researchers to investigate it and lead them to focus on the oil droplets capture and concentration process. Various theories such as plate-out theory [2], mixture theory [3], dynamic concentration model [4] and extended Reynolds equation with effective viscosity [5,6] have been proposed.

The existing theories of emulsion lubricated rolling process have contributed significantly to the understanding of lubricating property of emulsion. Nonetheless a complete analysis of the effects of oil concentration and droplet size in the emulsion on rolling parameters such as rolling pressure, film thickness, fractional contact area, and variation of oil concentration has not been reported elsewhere. This paper aims to study these effects and presents the result in practical terms.

2 THEORETICAL EQUATIONS

The paper considers mixed-film lubrication rolling process in which the analysis is divided into two active lubrication zones namely: work zone (WZ) $0 \leq x \leq x_1$ and inlet zone (IZ) $x_1 \leq x \leq x_a$. Furthermore the inlet zone (IZ) is divided into non-contact region (IZ1, full-film) $x_b \leq x \leq x_a$ and contact region (IZ2, mixed-film) $x_1 \leq x \leq x_b$, where x_a is the starting location of the hydrodynamic pressure and x_b marks the position where asperity on the strip starts to make contact with roll surface. Prior to the inlet zone oil droplets are captured in the conjunction. The effectiveness of the droplet capture process is represented by a capture coefficient (C) introduced by Schmid and Wilson [7]. In effect this coefficient defines the film thickness at the starting of the concentration process (h_s) i.e.

$$h_s = C\, d_s \qquad (1)$$

As there is little pressure increase and low water's pressure-viscosity coefficient it can be shown [7] that the oil concentration in the concentration region between x_a and the start of the concentration process (see Fig. 1) follows

$$h_s\, \lambda_{ds} = h\, \lambda_d \qquad (2)$$

From x_a hydrodynamic pressure starts to develop and we [8] have developed a concentration model based on the extended Reynolds equation of Yan and Kuroda [5,6].

$$\frac{\lambda_d}{\left(\frac{\lambda_c}{\eta\varphi} + \lambda_d\right)}(H_{t\_xa} - H_t) = \frac{(Z(1-R)+T)}{T(Z(1-R)+1)}\lambda_d H_t + C \qquad (3)$$

where H_t = non-dimensional average film thickness, H_{t_xa} = H_t at x_a, R = reduction ratio, T = non-dimensional strip thickness, Z = outlet speed ratio, λ_d = oil concentration, λ_c = water concentration and φ = non-dimensional lubricant pressure. Eq's. (1), (2) and (3) govern the oil concentration in the emulsion throughout the rolling zones shown in Fig. 1. The model describes variation of oil concentration at any point in the both inlet and work zones. C can be obtained from the boundary conditions for the oil concentration ie. $\varphi(Xa) = 1$, $\lambda_d(Xa) = \lambda_{dsa}$, and $H_t(Xa) = H_{t\_xa}$. Solution of Eq.(3) is a root finding problem. To obtain other rolling parameters these equations are solved simultaneously with Reynolds equation and equilibrium equation of the plastic flow of the strip.

<u>Inlet zone</u> $X_a \geq X \geq X_1$

In the inlet zone the strip velocity is constant. Thus from the Reynolds equation the lubricant pressure is governed by

$$\frac{d\varphi}{dX}=\frac{6RGS}{R*\phi H_t^3\left(\frac{\lambda_c}{\eta\varphi}+\lambda_d\right)}\left(H_{t\_xa}-H_t\right) \qquad (4)$$

where G = non-dimensional pressure coefficient, S = non-dimensional speed, ϕ = flow factor corrector.

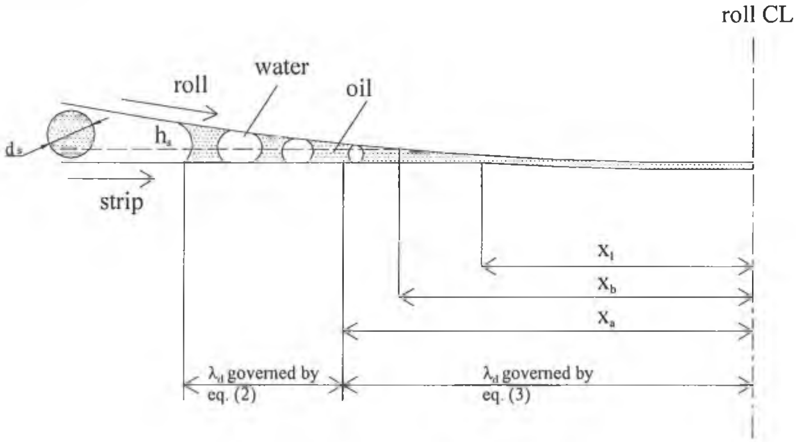


Figure 1: *Schematic of the rolling process and the concentration region*

<u>Work zone</u> $X_l \geq X \geq 0$
The lubricant pressure in the work zone is obtained by solving Reynolds equation, Eq. (5) together with the equations for interface pressure, Eq. (6) and asperity contact area, Eq. (7). Details of the numerical procedure can be found in [8].

$$\frac{d}{dX}\left(\phi H_t^3\left(\frac{\lambda_c}{\eta\varphi}+\lambda_d\right)\frac{d\varphi}{dX}\right)=\frac{6RGS}{R*(Z(1-R)+1)}\frac{d}{dX}\left(\left(\frac{Z(1-R)}{T}+1\right)H_t\right) \qquad (5)$$

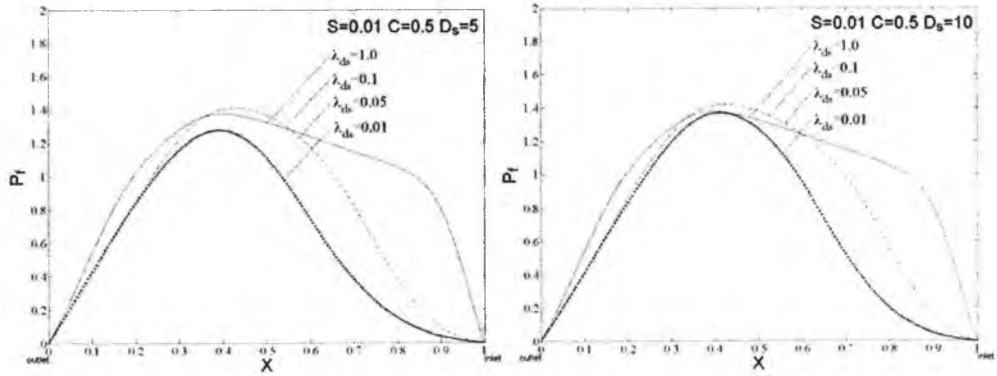
$$\frac{dP}{dX}=\frac{2RX}{T}+\frac{Ac\sqrt{Rr*}}{T}\operatorname{sign}(Z(1-R)-T)+\frac{2(1-A)RS(Z(1-R)-T)}{T^2H_t(Z(1-R)+1)}\left(\frac{\lambda_d}{\varphi}+\lambda_c\eta\right) \qquad (6)$$

$$\frac{dA}{dX}=-\frac{2XR}{\theta_a(2l*(1-A)+TE)} \qquad (7)$$

where A = fractional contact area, c = adhesion coefficient, E = non-dimensional strain rate [8] and θ_a = asperity slope. The numerical scheme has been validated with experimental results [9] in terms of rolling force obtained in emulsion lubricated rolling.

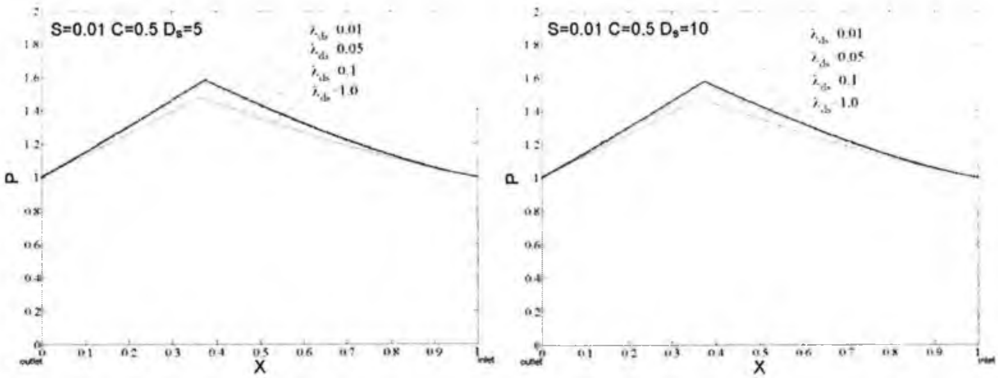
3 RESULTS AND DISCUSSIONS

The effects of oil concentration level of the emulsion and the droplet size are investigated at constant speed, S = 0.01 and constant capture coefficient, C = 0.5. These effects on hydrodynamic pressure, P_f are depicted in Figures 2. It is seen at this particular S and C for $\lambda_{ds} = 0.1$ and 0.05, the peak of P_f initially rises slightly above the neat oil's curve, $\lambda_{ds} = 1$. This is the consequence of starvation like effect associated with emulsion lubricated rolling causing higher total pressure, P as seen in Figures 2. However at lower $\lambda_{ds} = 0.01$, P_f curve is completely lower than that of neat oil's curve.



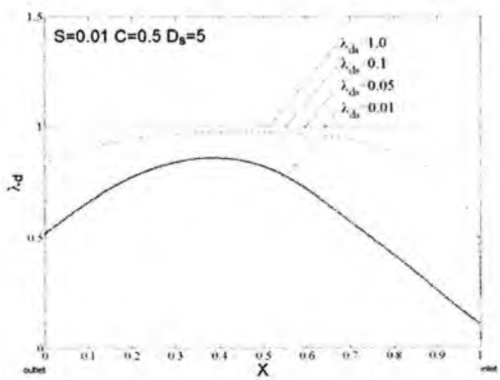
(a) (b)

Figure 2: *Hydrodynamic pressure (P_f) in the work zone.*



(a) (b)

Figure 3: *Total pressure (P) in the work zone.*



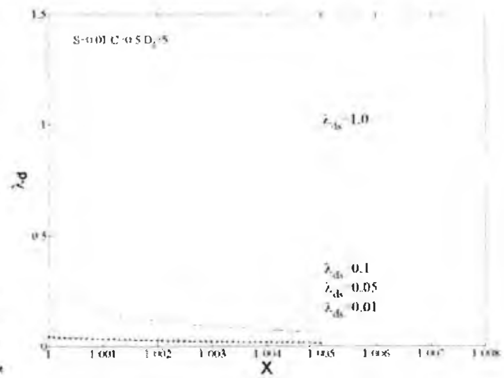
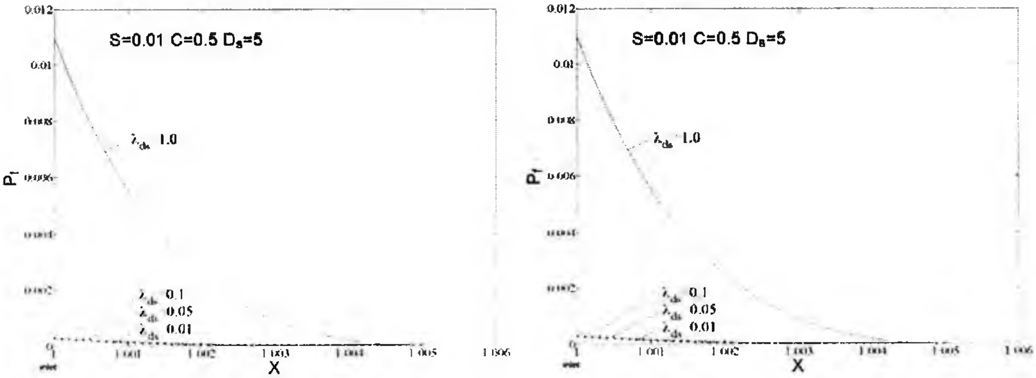


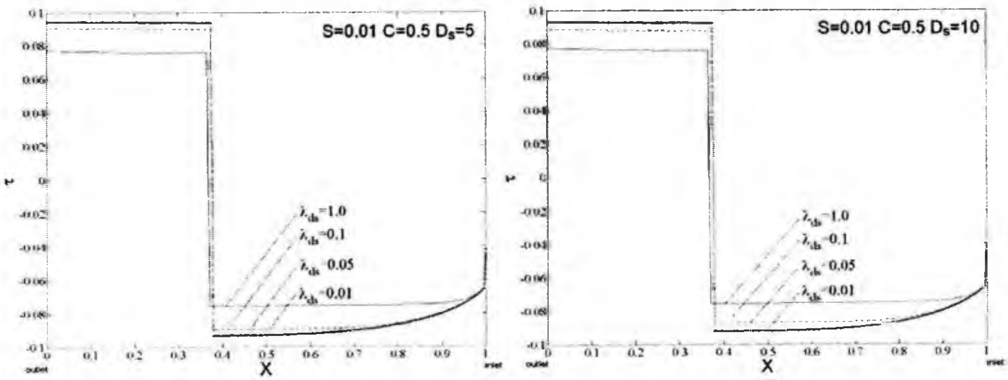
Fig. 4: *Oil concentration in the work zone* ***Fig. 5:*** *Oil concentration in the inlet zone*

The effects of λ_{ds} is more notable on P_f than on P with decreasing of λ_{ds} decreases P_f but increases P. Lower P_f of emulsion lubricated rolling could be attributed to the variation of λ_d in the work zone (Fig. 4). However with the oil concentration level is sufficiently



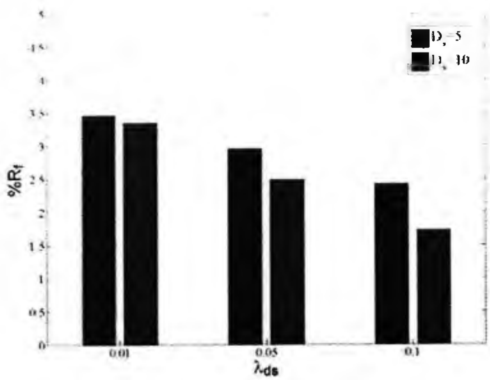
(a) (b)

Figure 6:*Hydrodynamic pressure (P_f) in the inlet zone.*



(a) (b)

Figure 7: *Friction (τ) in the work zone.*



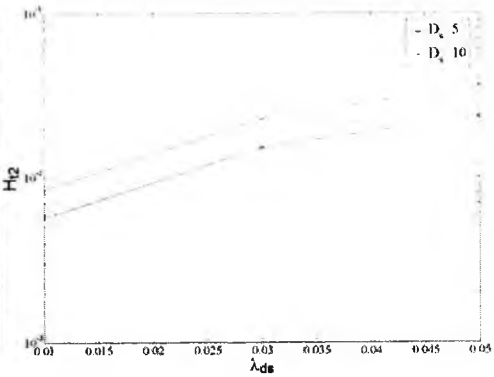


Fig. 8: *Percentage of rolling force increase* ***Fig. 9:*** *Effects of λ_{ds} and D_s on the H_{t2}*

high in most part of the work zone it may be argued that hydrodynamic pressure in the work zone should not be dependent on λ_{ds}. The explanation for this is that the development of P_f in the work zone begins in the inlet zone where λ_d is progressively being concentrated (Fig. 5) and markedly affects the gradient of P_f as shown in Figures 6. In terms of practical rolling force, which can be obtained upon integration of P curve throughout the work zone, it could be seen that decreasing λ_{ds} increases the percentage change of R_f from that of neat oil's case (Fig. 8).

The effect of λ_{ds} on local friction is illustrated in Figures 7. The increase of local friction is a reflection of increased fractional contact area, A, which increases with reduction of λ_{ds}. However the torque is found to be less affected by λ_{ds} than R_f. Figure 9 depicts the effects of λ_{ds} and D_s on the non-dimensional outlet film thickness, H_{t2} for 3 cases. This suggests that outlet film thickness could be controlled by either varying speed S or emulsion's oil concentration λ_{ds} or D_s.

4 CONCLUSIONS

When emulsion is used in strip rolling :

i. The effect of the oil concentration is predominantly seen in the development of the lubricant pressure whilst its effect on the total pressure is less pronounced.
ii. Lower emulsion oil concentration λ_{ds} increases rolling force R_f and this effect is exacerbated by droplet size, D_s.
iii. In addition to speed S, λ_{ds} and D_s could also be utilized to control the outlet film thickness, H_{t2}.

5 ACKNOWLEDGMENTS

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